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The effect of soil pH on phosphorus content of clover pasture

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The effect of soil pH on phosphorus content of clover pasture

Resource management technical report 417

The effect of soil pH on phosphorus content of clover pasture

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David Weaver, Robert Summers, David Rogers and Peta Richards

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Cover: Clover growing in a phosphorus trial.

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Summary

Testing of pasture soils from 2009 to 2018, as part of DPIRD's Whole Farm Nutrient Mapping (WFNM) project in the coastal catchments of south-west Western Australia (WA), indicated that soil pH was so low it could be limiting plant access to nutrients. Observations by some farmers who had been involved in the soil testing were that lime application had not increased pasture production, even when pH_{Ca} (pH measured in calcium chloride) tests indicated that phosphorus (P) should become more available by increasing soil pH. Farmers also wanted to know if they needed to apply more P than soil testing suggested to overcome effects that soil acidity might have on reducing P uptake by pasture plants.

We hypothesised that the acid soils were more than adequately fertile in P, despite their low pH, and subterranean clover (*Trifolium subterraneum*) would still have access to enough P. If pastures can take up sufficient P, farmers might not need to apply lime to such soils to ensure P availability to pastures. Nor would they need to apply more P to overcome the effect of pH on P uptake. Poorly utilised P in the coastal catchments is transported in run-off and contributes to algal blooms in watercourses and estuaries, and unnecessary P application could increase input costs and the amount of P in run-off.

About 80% of tested paddocks had a pH_{Ca} less than 5.5. As pH_{Ca} falls below 5.5, the ability of pasture plants to take up P is likely to decrease because of a potential reduction in availability for uptake by plants. The soil testing also showed that about 80% of paddocks contained ample soil P-fertility, and about 60% contained ample soil P-fertility as well as being acidic (pH_{Ca} <5.5).

We used the results of the WFNM project to identify sites which had a range of soil P-fertility and pH_{Ca} levels, and we undertook tissue testing of clover plants to estimate the soil P-fertility required to avoid lime application.

For soils of similar P-fertility, increasing pH was associated with higher P uptake by clover, but these were not always significant ($P \leq 0.05$). In soils with excessively high P-fertility, clover plants took up more P than needed for optimum production, regardless of soil pH_{Ca}. However, while most of the soils tested had higher P-fertility than necessary for clover production, there may be other constraints that are caused by soil acidity or other conditions which can limit plant yield, such as high subsoil aluminium, poor clover nodulation, waterlogging, compaction or micronutrient deficiencies.

When there was 90% more P in the soil than was required (that is, 1.9 times the required soil P-fertility), soil pH_{Ca} had little effect on the amount of P taken up by clover. Forty per cent of soil samples taken in the WFNM project had at least 90% more soil P-fertility than required, which means soil acidity is not affecting P uptake. Adding lime in these situations would only lift production if constraints other than P-fertility exist.

The results suggest there is unlikely to be any significant benefit on clover P concentration by liming soils with a pH_{Ca} of 5.0 or above and with at least 20% more soil P-fertility than required for optimum production. This does not mean that liming is not beneficial because nutrients other than P can benefit from improved soil pH. It does, however, help to explain why some farmers may not have achieved an increase in clover production by applying lime.

This report also provides a table of adjusted critical Colwell P values for soils with pH_{Ca} less than 5.0 to enable recommendations for P applications to be adjusted for pH.

1 Introduction

From 2009 to 2018, DPIRD's WFNM project tested pasture soils on farms in the coastal catchments of the south-west of WA to improve productivity while helping to address the problem of P leaving farmland and causing algal blooms in the waterways and estuaries. Results from the soil testing program indicated that soil pH was so low it could be limiting plant access to nutrients.

During the soil testing program, some farmers expressed concern that liming soils to increase soil pH was not leading to expected increases in pasture production. When soil pH is low, it is possible that nutrients, such as P, may become less available and limit production. Applying additional P, which is an option for managing acid-induced nutrient deficiency, may be required even where soil tests indicate there is more than sufficient P in the soil for plant uptake (Moore et al. 1998, Truog 1948).

We hypothesised that the acid soils were more than adequately fertile in P, and despite their low pH, subterranean clover (*Trifolium subterraneum*) would still have access to enough P because of the overabundant supply of P. We wanted to quantify the soil P-fertility level required in low pH soils to ensure P uptake was not limited. To determine this we undertook tissue testing of pasture plants to examine the nutrient concentration of clover shoots in paddocks containing known ranges of soil pH_{Ca} and soil P-fertility. If we found that soil pH affected P uptake, an ancillary aim was to adjust the critical Colwell P levels to take account of the pH_{Ca} if soil pH was not going to be corrected.

2 Background

Interactions between soil pH, soil fertility and nutrient availability within clover pastures can be complex. Current understanding suggests soil pH_{Ca} needs to be between 5.5 and 7 to ensure optimum nutrient availability for plants (Figure 2.1). As pH_{Ca} falls below 5.5, many of the major nutrients may become less available for plant uptake.

Soil testing of pasture soils in the south-west of WA suggested soil pH could be limiting plant nutrient availability, with about 80% of the 28 000 paddocks tested showing a soil pH_{Ca} less than 5.5 (Figure 2.1). Based on current critical values, the soil testing also showed that about 80% of paddocks contained ample soil P-fertility, and about 60% contained ample soil P-fertility while also being acidic (pH_{Ca} <5.5). These findings are supported by other studies in WA and Australia (Gourley et al. 2019, Weaver & Wong 2011).

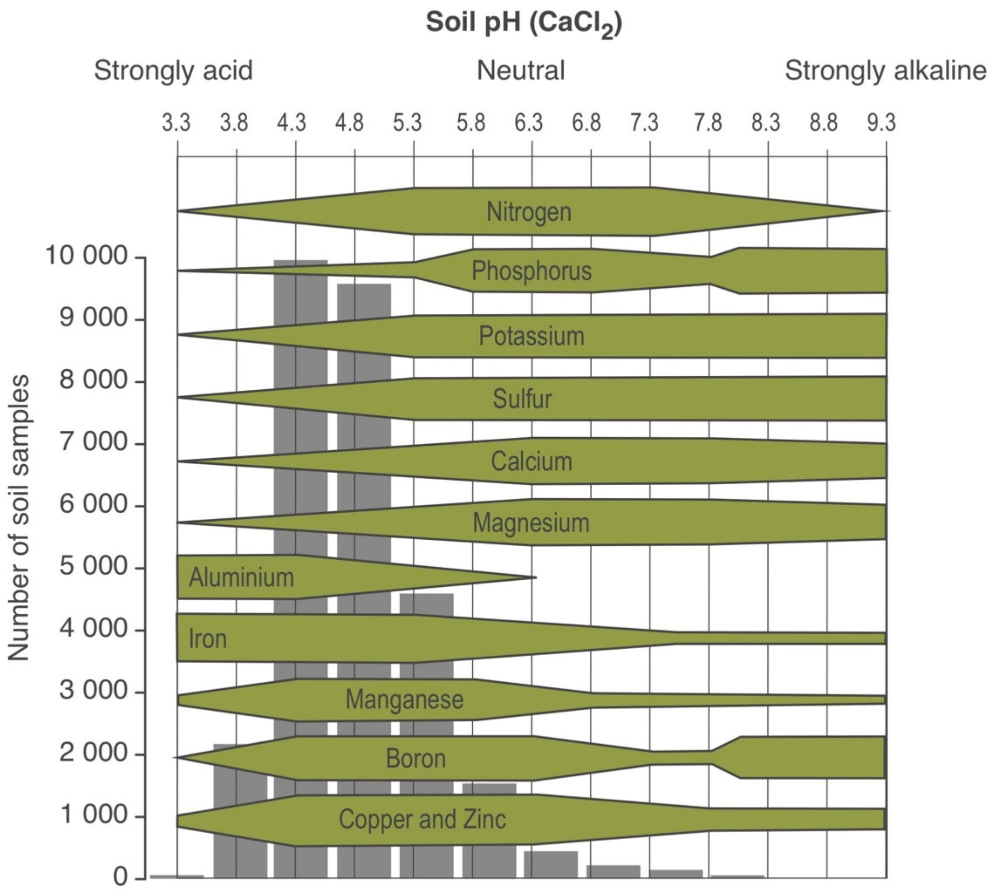


Figure 2.1 The effect of soil pH_{Ca} on the relative availability of nutrients to plants (adapted from (Truog 1948)) overlain on the pH distribution of 28 000 surface soil samples collected from the coastal plain in south-west WA

There is potential that soil P-fertility levels may not account for the influence of acidity on P uptake. Low soil pH could potentially reduce the availability of P to plants across all ranges of P-fertility, including soils containing sufficient P. Studies have shown that the addition of P reduced the impact of pH which would otherwise have reduced the yield of crops and pastures (Scanlan et al. 2017).

However, anecdotal evidence from farmers suggested that while significant investment in lime had lifted soil pH, there did not appear to be any positive impact on pasture production. This observation could be due to a range of factors, including:

- soils with low aluminium levels may be widespread in the WFNM project area and hence unlikely to benefit from lime
- the observation being limited by not being controlled for other confounding factors, such as induced micronutrient deficiencies with liming
- the observation may have been over a shorter timeframe than that needed for the lime to react with the soil
- lime applications may have been insufficient and may not have lifted pH enough to improve uptake of essential nutrients
- the soils may contain more nutrients, such as P, than required for optimum nutrient availability and they may be sufficiently available, despite the low pH.

Concern over an increased P requirement in acidic soils is justified because while acidity affects root growth through aluminium toxicity, it has been shown that applying P can reduce the effect of acid-induced yield reduction of crops and pastures (Edwards 1991, Miles & Eckard 1991, Munns 1965, Shoop et al. 1961).

The WFNM project was extended to include an assessment of the uptake of P and other nutrients by pasture. We used field survey data rather than a trial testing lime application on P uptake and yield because so many sites had been soil tested and we were able to select sites where the pH_{Ca} and soil P-fertility covered a large enough range to examine effects and interactions on uptake by pastures. For our study, pH_{Ca} levels less than 5.5 were considered acidic.

3 Methods

Paddocks were sampled in the WFNM project from 2009 to 2018 using a 19mm diameter core sampler consisting of 30 subsamples. Samples were analysed for:

- electrical conductivity (EC) and pH_{Ca}, which were determined after extracting soil for one hour with deionised water and 0.01 molar calcium chloride solution, respectively, at a soil solution ratio of 1:5 (Rayment & Higginson 1992, Rayment & Lyons 2010, Schofield & Taylor 1955)
- Colwell P and Colwell K (potassium; Colwell 1965)
- phosphorus buffering index (PBI), which was the result of incubating the sample in a 1000µg P/mL (micrograms of P per millilitre) solution and correcting for the Colwell P (Burkitt et al. 2002)
- sulfur (S) using the KCl-40 S test, in which S was extracted by a 0.25 molar potassium chloride (KCl) solution at 40°C for three hours (Blair et al. 1991).
- organic carbon (for the SWCC samples), which was estimated using the heat of the dilution method of Walkley and Black (1934).

In 2014–15, we selected samples from a factorial combination of four pH_{Ca} groups (<4.5, ≥4.5–<5.0, ≥5.0–<5.5, ≥5.5) and 10 P-fertility groups (<0.4, ≥0.4–<0.6, ≥0.6–<0.8, ≥0.8–<1.0, ≥1.0–<1.2, ≥1.2–<1.4, ≥1.4–<1.6, ≥1.6–<1.9, ≥1.9–<3.0 and ≥3.0).

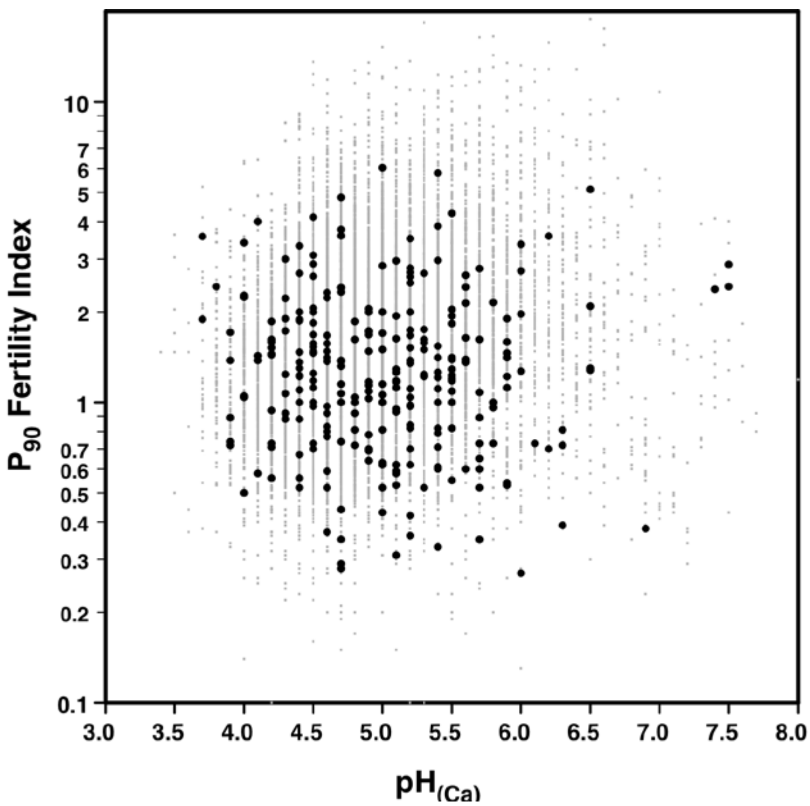
The P-fertility groups were identified using a P index (Cope & Rouse 1973, Simpson et al. 2011) — a ratio of measured soil Colwell P to a 'reference' or 'critical' soil Colwell P (Bolland et al. 2010, Gourley et al. 2007, Gourley et al. 2019). In our study the index was referenced to 90% relative pasture yield (P_{90}), where P_{90} fertility indices of 0 to 1 were considered P deficient, and those greater than 1 were considered to contain more P than required to achieve 90% relative pasture yield. For example, a soil with a P_{90} fertility index of 2 was considered to contain twice the P required to reach 90% relative pasture yield.

The soil Colwell P and PBI were used with response curves derived from Better Fertiliser Decisions from Gourley et al. (2007) and Gourley et al. (2019) to determine the target Colwell P required for each soil sample to achieve 90% relative pasture yield. The measured soil Colwell P was divided by the critical Colwell P to derive the P_{90} fertility index.

Five randomly selected paddocks were identified for each pH_{Ca} and P_{90} fertility index group. This resulted in up to 200 sites covering a range of pH_{Ca} and P_{90} fertility index groups from which clover samples could be harvested and analysed (Figure 3.1).

To avoid potential complications associated with deficiencies of macronutrients other than P, a subset of the selected paddocks were chosen so that the five randomly selected paddocks contained sufficient K and S. Ideally the selected paddocks should have contained all nutrients in sufficient supply, except for P at the specified fertility index levels; however, data for all nutrients was not available in the soil test data.

Where five paddocks within each of the pH_{Ca} and P_{90} fertility index groups using the WFNM dataset could not be identified, paddocks identified during a soil and tissue sampling program undertaken by the SWCC were included. The resulting dataset contained 232 sites (Figure 3.2).



Note: The larger black dots are the soil sample sites selected for tissue testing and the smaller grey dots are the remaining sample sites from the WFNM project.

Figure 3.1 The distribution of the P_{90} fertility index relative to pH_{Ca}

To simplify analysis, we aggregated the pH_{Ca} groups (<5.0, ≥5.0–<5.5 and ≥5.5) and the P_{90} fertility index groups (<0.6, ≥0.6–<1.2, ≥1.2–<1.9 and ≥1.9). This reduced data noise and provided greater confidence in results with a greater number of samples in each group. Analysis of variance between each of the factors was undertaken to explore how soil pH_{Ca} influenced P concentrations in clover samples for different P_{90} fertility index groups.

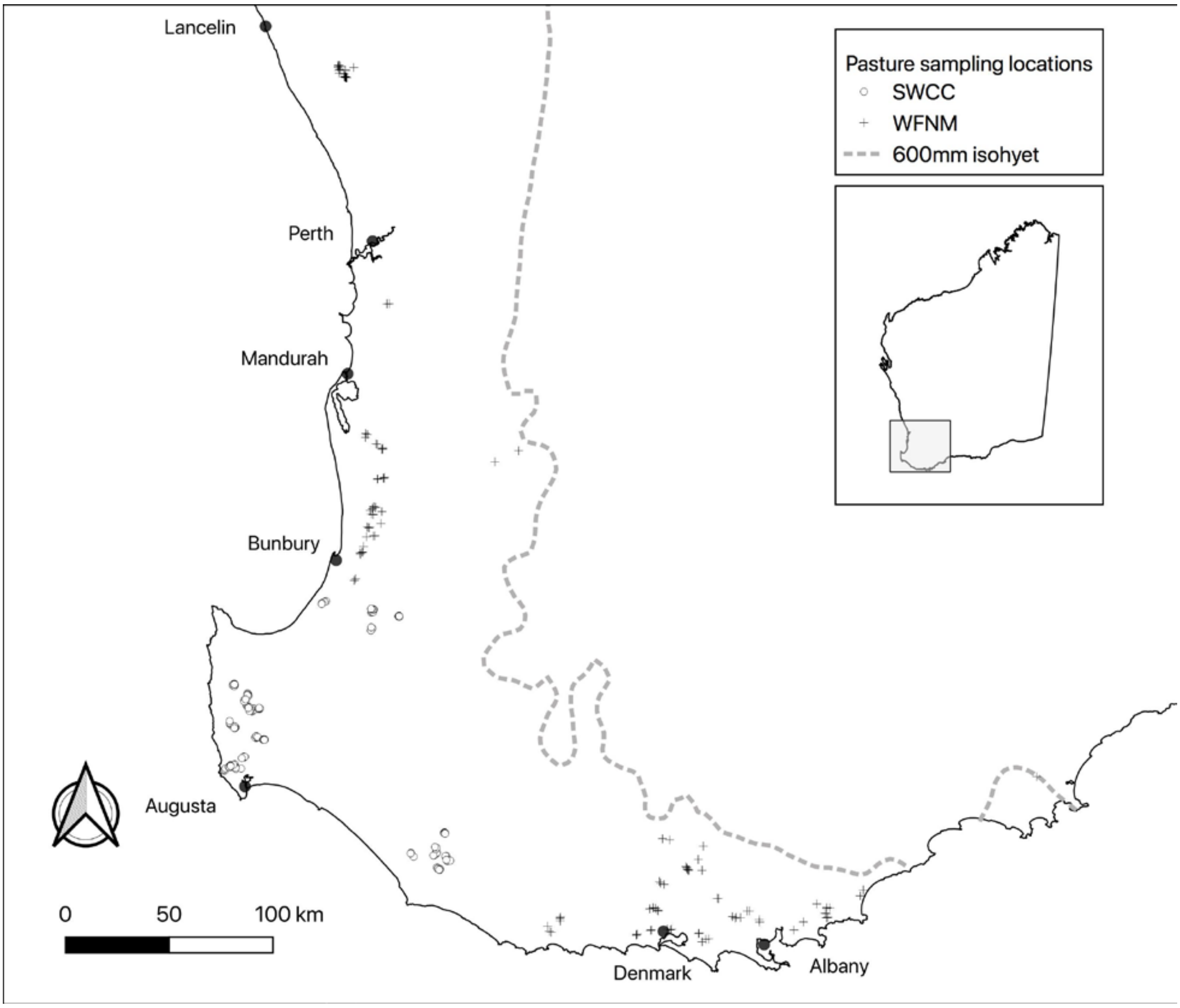
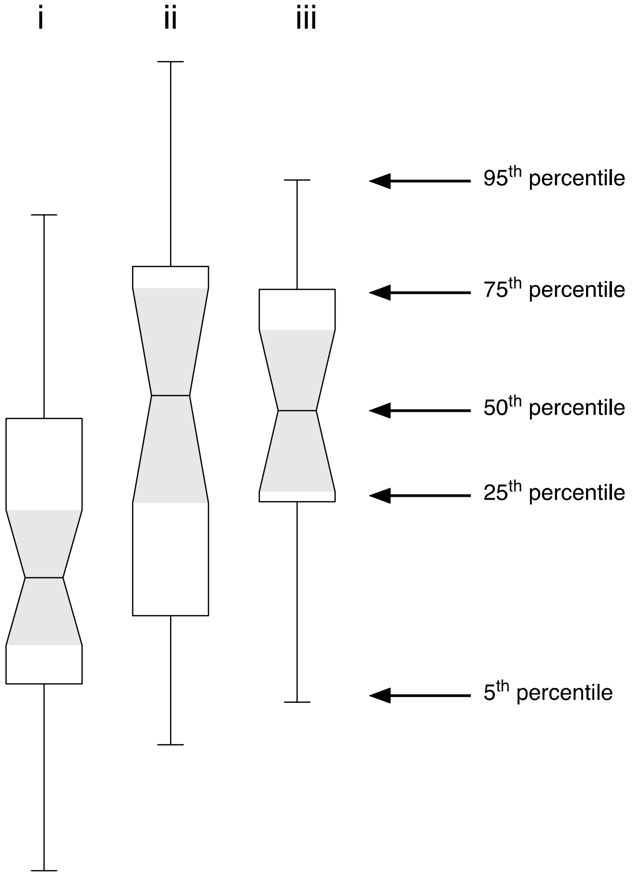


Figure 3.2 Location of pasture sampling sites in the WFNM and SWCC projects

We used notched box and whisker plots to show the distribution of clover P concentrations for each combination of pH_{Ca} and P_{90} fertility index groups (Figure 3.3). Box and whisker plots represent percentiles, with the lower whisker showing the 5th percentile (5% of the data is less than this value and 95% of the data is greater than this value). This same logic applies to various locations on the box plot; for example, the 50th percentile has 50% of the data points above this point and 50% of the data points below.

The notched area on the plots can be visually compared with other box plots to explore differences between factors or treatments. McGill et al. (1978) explain that in the absence of a formal statistical test, when notches do not overlap, the median values are “approximately, significantly different”. While providing a good visual comparison, the box and whisker plot only approximates significant difference, so we also conducted a formal analysis of variance.



Note: Shaded sections show ‘notches’. In the absence of a formal statistical test, a visual assessment of significant difference can be approximated when notches of box and whisker plots that are being compared do not overlap. In this figure, i and ii and i and iii are approximately significantly different, while ii and iii are not.

Figure 3.3 Anatomy of notched box and whisker plots

Reuter and Robinson (1997) classified clover P concentrations as low, marginal or adequate. They defined ‘adequate’ P as the concentration at 100% of relative pasture yield, so their definition of marginal concentration is likely to be more than sufficient to support clover growth for most grazing enterprises or at a P_{90} fertility index of 1.

To explore the relationship with other nutrients, we then prepared a correlation matrix of tissue and soil test data to determine the linear correlation (negative or positive, $P \leq 0.05$) between variables (Appendix A). Appendix B contains the raw data from the plant tissue and soil testing.

4 Results and discussion

4.1 pH and phosphorus

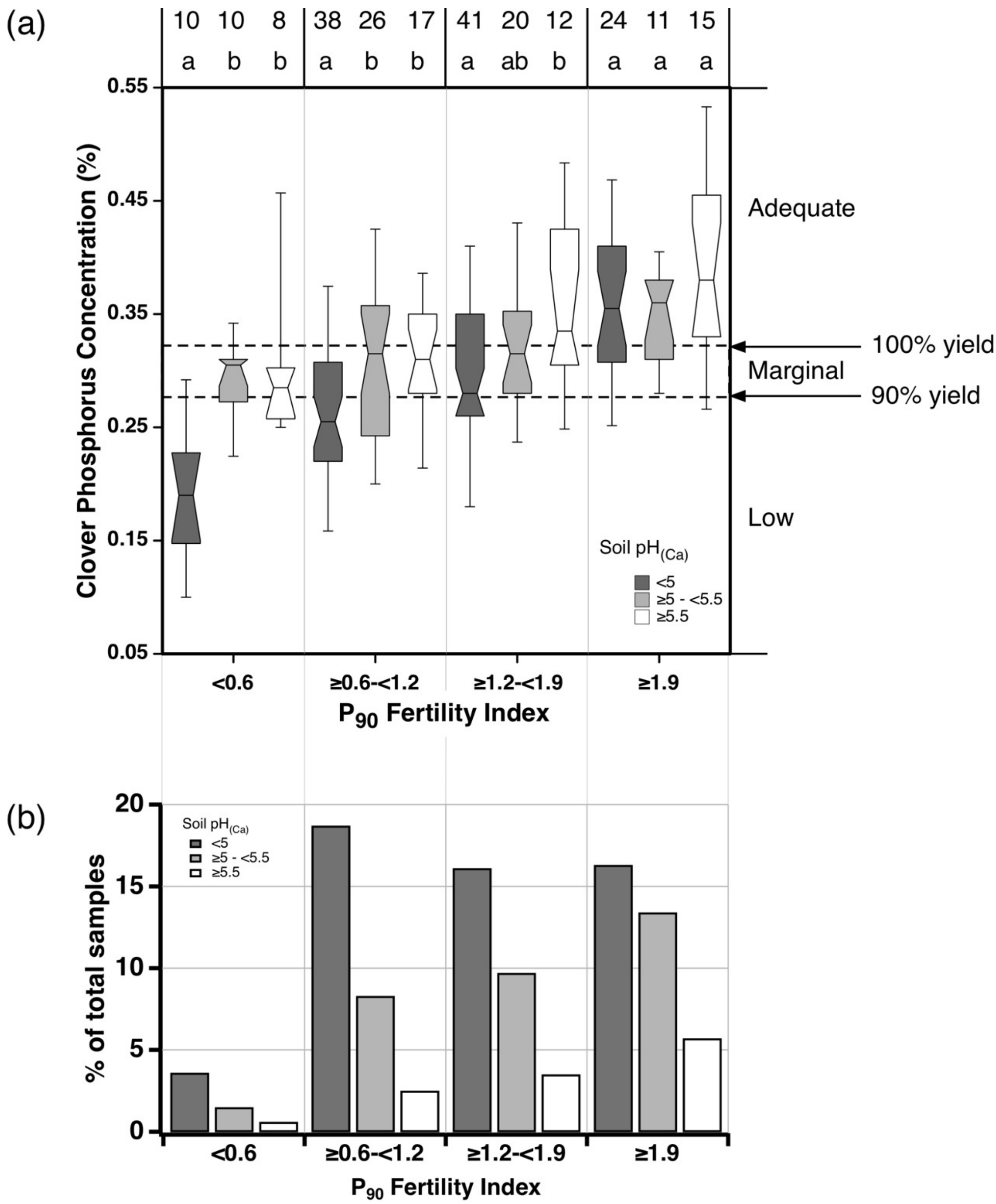
Phosphorus concentration in clover tissue increased with P_{90} fertility index (Figure 4.1a). Phosphorus concentrations in the clover tissue ranged from low to marginal when the soil P_{90} fertility index was less than 0.6, through to adequate when the soil P_{90} fertility index was 1.9 or greater. Since Reuter and Robinson (1997) defined adequate P as being equivalent to 100% of maximum yield, the 'adequate' levels used in our study in Figure 4.1a are likely to exceed plant requirements because our analysis was referenced to 90% relative pasture yield. It is not necessary to achieve a P_{90} fertility index of 1.9 or greater to have sufficient P uptake for pastures.

The agronomic optimum we used may be substantially more than the economic optimum, but this needs to be assessed against the economics of each landholding. The agronomic optimum concentration of P in the soil is also above the environmental threshold for water quality in run-off (Gourley & Weaver 2012, McDowell et al. 2020).

When the soil P_{90} fertility index was less than 0.6, there was a significant increase ($P \leq 0.05$ is used throughout) in clover P concentration when soil pH_{Ca} increased from less than 5.0 to 5.0 or greater, but no significant difference when soil pH_{Ca} increased from 5.0 to 5.5 or greater. Results were similar for P_{90} fertility index of 0.6 or greater to less than 1.2 (≥0.6–<1.2), with significant differences in clover P concentration only between pH_{Ca} less than 5.0 and 5.0 or greater. At the higher soil P_{90} fertility index of 1.2 or greater to less than 1.9 (≥1.2–<1.9), there was no significant difference in the clover P concentrations between soil pH_{Ca} less than 5.0 (<5.0) and 5.0 or greater to less than 5.5 (≥5.0–<5.5), or pH_{Ca} 5.0 or greater to less than 5.5 (≥5.0–<5.5) and 5.5 or greater (>5.5). However, there was a significant difference between pH_{Ca} less than 5.0 and pH_{Ca} 5.5 or greater. At a soil P_{90} fertility index of 1.9 or greater, soil pH had no significant effect on clover P concentration.

The results show that increasing soil pH_{Ca} above 5.0 in a soil with a P_{90} fertility index of 1.2 or greater is unlikely to increase clover P concentration. About 70% of all samples collected in the WFNM project had a P_{90} fertility index of 1.2 or greater, and a further 30% had a P_{90} fertility index of 1.2 or greater and a pH_{Ca} of 5.0 or greater (Figure 4.1b). This does not mean that liming will not benefit these soils because factors other than P, such as clover nodulation, may benefit from lifting soil pH. Production may increase with increasing pH in these circumstances, but P uptake may not.

The results do, however, help to explain why some farmers have not seen an improvement in clover production when applying lime to soils with a pH_{Ca} of 5.0 and above. The soils contain P-fertility well in excess of plant requirements, so that the clover is able to access enough P despite the low pH. This means the quantity of excess soil P-fertility is much greater than the reduction in the quantity of soil P-fertility due to acidity — the effect of excess soil P enabling P uptake is greater than the effect of pH reducing P uptake.



Notes for a):

1. Dashed lines show the marginal range of P concentrations for clover in relation to relative yield (Reuter & Robinson 1997).

2. Within each P_{90} fertility index group, notched box plots with different letters are significantly different and increase in clover P concentration alphabetically.

3. Numbers above each notched box plot denote the number of samples (n) for that combination of pH_{Ca} class and P_{90} fertility index group.

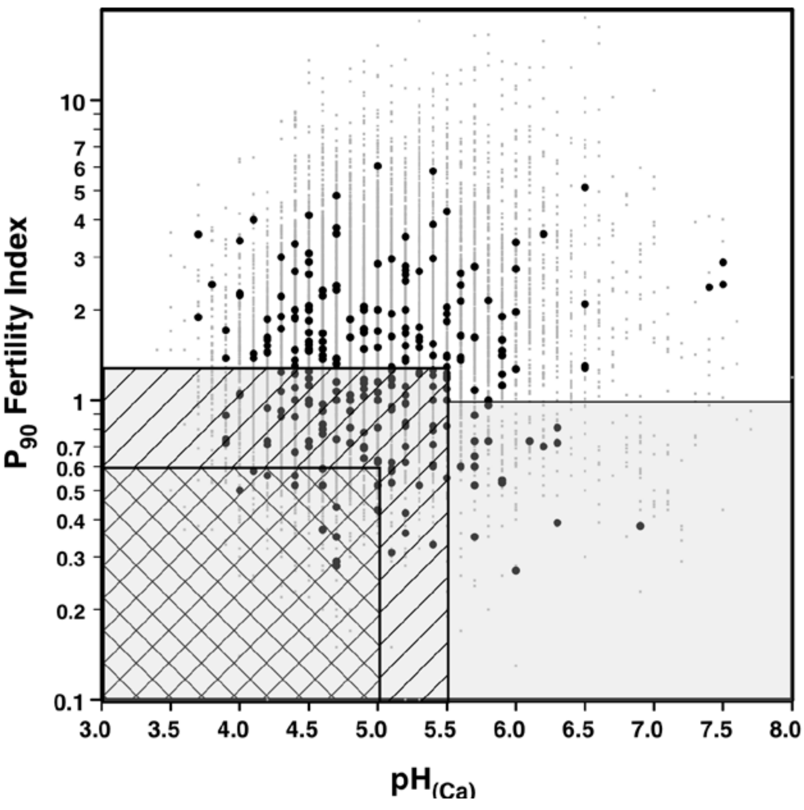
Figure 4.1 a) Notched box and whisker plots of clover P concentration for soils with various pH_{Ca} and P_{90} fertility index ranges; b) Percentage of soil samples from the WFNM project contributing to soil pH ranges within each P_{90} fertility index group

The median P_{90} fertility index value of the WFNM and SWCC samples was 1.6, with 80% of all samples having a P_{90} fertility index greater than 1. Forty per cent of all samples collected in the WFNM project had a P_{90} fertility index of 1.9 or greater (Figure 4.1b). Given that P_{90} fertility index only needs to be 1 to supply sufficient P for clover production, these paddocks would not require P applications, provided soil pH is high enough. Funds set aside for P could therefore be used on other fertilisers or soil amendments.

Only about 3% of paddocks sampled in the WFNM project had low levels of soil P-fertility (P_{90} fertility index less than 0.6) and a pH_{Ca} less than 5.0 (Figure 4.1b, Figure 4.2). These paddocks could be limited in P for clover production; liming, as well as P application, would likely improve P uptake in these soils.

Our study confirmed that many soils contain more nutrients, such as P, than plants require and these might be sufficiently available despite the low pH. We also identified:

- where correction of soil pH is highly likely or moderately likely to improve the uptake of P by clover without the addition of more P (Figure 4.2)
- the pH_{Ca} and P_{90} fertility index ranges in which the application of P and/or lime will improve the P content of clover pastures (Figure 4.2).



Note: The larger black dots are the soil sample sites selected for tissue testing and the smaller grey dots are the sample sites from the WFNM project. The grey shaded area shows where P is required to meet plant demand if soil pH is not corrected. The cross-hatched area shows where it is highly likely that increasing soil pH will result in increases in clover P content. The diagonally hatched area shows where it is moderately likely that increasing soil pH will result in increases in clover P content.

Figure 4.2 Distribution of the P_{90} fertility index relative to pH_{Ca} and the likelihood of response to P and lime

The findings of our study can be applied to previously published critical Colwell P values (Gourley et al. 2019). These values at different levels of relative pasture yield for soils of varying PBI without any constraints can be compared with those where soil pH_{Ca} is less than 5.0 (Table 4.1). This adjustment provides critical soil test values where the only constraint is soil acidity.

Table 4.1 Published critical Colwell P values at different levels of relative pasture yield for soils of varying phosphorus buffering index without any constraints, and the adjusted values for soils where pH_{Ca} is less than 5.0

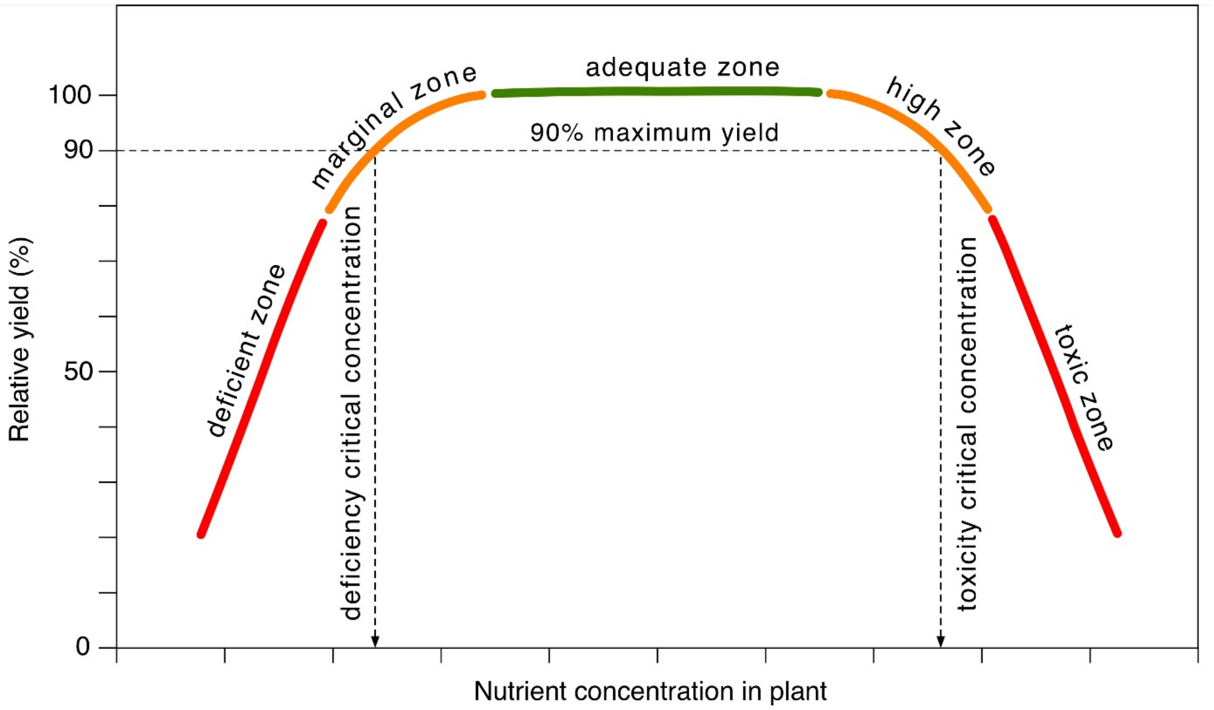
Phosphorus buffering index		Critical Colwell P values at different levels of relative yield*				Adjusted critical Colwell P values for soil pH <5.0 at different levels of relative yield			
Value	Description	95%	90%	85%	80%	95%	90%	85%	80%
<5	Extremely low	10	8	7	6	12	10	7	6
≥5–<10	Very low	15	11	10	8	18	13	11	10
≥10–<15	Low	20	15	13	11	24	18	14	13
≥15–<35	Moderately low	25	20	16	14	30	24	19	17
≥35–<70	Medium	29	22	18	16	35	26	22	19
≥70–<140	Moderately high	34	25	21	18	40	30	25	22
≥140–<280	High	40	30	25	21	47	36	29	25
≥280–<840	Very high	55	42	35	30	66	50	42	35

* Values from (Gourley et al. 2019)

4.2 Other nutrients

Along with soil pH, other nutrients can also influence plant uptake of P. Our study was based on sampling plant tissue at sites that had sufficient K and S soil levels, although around 20% of each showed some deficiency. Similarly, we selected sites to find enough samples in each pH_{Ca} and P_{90} fertility index group. Therefore, we did not randomly select sites. This is a reasonable approach given the questions we sought to answer. So, while data for nutrients other than P was not available for all selected sites, the clover tissue test results did provide insight into the general nutrition of clover pastures in south-west WA. Appendix B contains the raw tissue and soil test data to enable further use of the data and to re-evaluate the data should the zones in Reuter and Robinson (1997) change with further information.

Figure 4.3 summarises the plant tissue nutrients we examined aligned with their ideal range, based on Reuter and Robinson (1997). These nutrients were classified as deficient, marginal, adequate-to-high or toxic, and the percentage of relative yield within each. It is important to note that the definition of ‘adequate’ in Reuter and Robinson (1997) is based on 100% of relative pasture yield. Economics means that aiming for the upper half of the marginal zone through to the adequate zone (90–100% relative pasture yield) should be sufficient for clover pastures in most situations.



Nutrient	Deficient	Marginal	Adequate - High	Toxic
Boron	6.5	89.4	4.1	
Calcium	4.5	6.5	89.0	
Chloride			88.2	11.8
Copper	4.9	11.8	83.3	
Iron			100.0	
Magnesium	1.2	69.4	29.4	
Manganese	4.9	6.5	88.6	
Nitrate	73.1	20.8	6.1	
Nitrogen	0.8	33.1	66.1	
Phosphorus	33.9	20.0	46.1	
Potassium	20.4	53.1	26.5	
Sodium			83.7	16.3
Sulphur	21.2	26.9	51.0	0.8
Zinc	0.4	4.5	85.3	9.8

Note: The tabular section aligns with the nutrient status (adapted from Reuter and Robinson (2007)) in the top of the figure.

Figure 4.3 The yield and nutrient concentration aligned with a table showing the percentage of clover samples in each of the nutrient status zones

About 5% of plant tissue samples were deficient in boron, copper and manganese (Figure 4.3); a situation that could be overcome by applying these micronutrients. Less than 1% of samples showed zinc deficiency, probably because zinc is a trace impurity in superphosphate and is often being applied as an unrealised side benefit of applying superphosphate.

Soil tests cannot accurately assess micronutrient availability to plants, so tissue testing is needed to identify deficiencies of these nutrients.

Correlations between the tissue test and soil test data showed significant ($P \leq 0.05$) linear trends (Appendix A). There was a negative correlation between soil pH_{Ca} and tissue concentrations of copper, manganese, magnesium and zinc — for example, as pH_{Ca} increased, these tissue concentrations decreased — with all but copper being significant. Tissue calcium had a positive correlation with pH_{Ca}, probably because liming increased calcium ions while reducing the availability of copper, manganese, magnesium and zinc. While liming can have a wide range of production benefits, its immediate impact on micronutrients, especially if they are already in the lower part of the marginal range, could limit the effectiveness of liming in improving plant production.

Tissue testing is an important management practice, especially when liming. The productivity increase from liming may not reach its full potential if micronutrients are not available.

Many other strong correlations were seen in the tissue and soil test data:

- There was a positive correlation between PBI and Colwell P, suggesting soils with higher PBI also have higher Colwell P, which is consistent with other research, such as (Weaver & Reed 1998).
- There was a positive correlation between PBI and KCl-40 S, which is consistent with the historical use of P sorption parameters, such as reactive iron (Angell 1999), as a surrogate for S response in soils, before the development of S soil tests.
- There was a positive correlation between Colwell P and Colwell K, which is consistent with a positive correlation between PBI and Colwell K. Increased critical Colwell K values have been associated with increased soil texture fineness (Gourley et al. 2019), which is also associated with increased soil PBI. Soils with higher PBI are able to retain more P and K.
- There were positive correlations between plant tissue P, K and S and their soil test counterparts, which is consistent with pasture response curves (Gourley et al. 2007, Gourley et al. 2019).

5 Conclusion

Soil acidity could be restricting the P content of a small percentage (<3%) of clover pastures in the high rainfall, coastal area of south-west WA. Low levels of tissue P are most likely in soils with a P_{90} fertility index of less than 0.6 and a pH_{Ca} less than 5.0. For soils with pH_{Ca} less than 5.0, we were able to adjust the critical Colwell P values to allow for the impact of low pH on P uptake.

Most of the paddocks sampled in coastal area of south-west WA have a P_{90} fertility index of 1.2 or greater and should contain enough P to maintain clover P concentrations in the marginal to adequate range, even when the soil is acidic. This assumes no other production constraints and no other benefits from adding lime. This might not be a reasonable assumption because acidic conditions can limit nodulation for nitrogen fixation in legumes and create aluminium toxicity sufficient to limit root growth.

Micronutrient deficiency in clover was found at a number of sites and it is likely that some of the sites with marginal micronutrient levels may become deficient after application of lime. Tissue testing should assist to identify these instances.

Tissue testing is a useful adjunct to soil testing, and both are required to make evidence-based fertiliser and farm management decisions. Given that fertilisers represent around 25% of farm input costs, investing in tissue and soil testing is prudent and cost effective.

Appendix A Correlation matrix for tissue and soil test data

Table A1 Correlation matrix for tissue and soil test data

Parameter	Total nitrogen	Nitrate	Phosphorus	Potassium	Sulfur	Copper	Zinc	Manganese	Magnesium	Iron	Boron	Sodium	Chloride	Calcium	*Colwell P*	*PBI*	*Colwell K*	*pH_{Ca}*	*Ammonia*	*KCl-40 S*	*OC*	*EC*
Total nitrogen	1.000																					
Nitrate	0.214	1.000																				
Phosphorus	0.356	0.248	1.000																			
Potassium	0.129	0.391	0.415	1.000																		
Sulfur	0.475	0.323	0.451	0.322	1.000																	
Copper	0.181	–0.055	–0.212	–0.187	0.124	1.000																
Zinc	0.250	–0.045	0.107	–0.064	0.023	0.227	1.000															
Manganese	–0.154	0.006	0.040	–0.022	0.049	0.197	0.005	1.000														
Magnesium	–0.114	–0.054	0.066	0.065	–0.122	–0.244	0.118	–0.055	1.000													
Iron	0.015	–0.030	–0.004	–0.037	0.099	0.192	–0.100	0.063	–0.172	1.000												
Boron	0.243	–0.271	–0.359	–0.302	–0.313	0.135	0.233	–0.307	0.251	–0.063	1.000											
Sodium	0.046	–0.106	–0.154	–0.530	0.041	0.074	0.014	–0.007	0.105	–0.098	0.269	1.000										
Chloride	–0.069	0.360	0.339	0.420	0.415	–0.260	–0.182	0.067	0.090	–0.131	–0.517	0.245	1.000									
Calcium	–0.025	–0.197	–0.253	–0.306	–0.200	–0.201	0.072	–0.402	0.175	–0.176	0.499	0.132	–0.221	1.000								
Colwell P	*0.212*	*0.166*	*0.274*	*0.181*	*0.212*	*0.139*	*0.007*	*0.010*	*–0.165*	*0.089*	*–0.085*	*–0.025*	*0.090*	*–0.066*	*1.000*							
PBI	*0.210*	*0.116*	*–0.071*	*0.004*	*0.229*	*0.361*	*–0.040*	*0.145*	*–0.230*	*0.123*	*–0.026*	*0.141*	*0.095*	*–0.267*	*0.356*	*1.000*						
Colwell K	*0.070*	*0.015*	*0.085*	*0.277*	*0.010*	*0.143*	*0.018*	*0.055*	*0.067*	*0.084*	*0.097*	*–0.279*	*–0.192*	*–0.090*	*0.374*	*0.174*	*1.000*					
pH_{Ca}	*0.135*	*0.140*	*0.286*	*0.142*	*0.219*	*–0.116*	*–0.263*	*–0.199*	*–0.195*	*0.184*	*–0.120*	*–0.150*	*0.099*	*0.136*	*0.098*	*–0.001*	*0.060*	*1.000*				
Ammonia	*0.135*	*0.000*	*–0.016*	*0.093*	*0.055*	*0.157*	*0.261*	*0.150*	*0.085*	*–0.079*	*0.074*	*–0.114*	*–0.091*	*–0.128*	*0.092*	*0.311*	*0.552*	*–0.284*	*1.000*			
KCl-40 S	*0.150*	*0.173*	*0.072*	*0.158*	*0.240*	*0.051*	*–0.089*	*0.059*	*–0.214*	*0.001*	*–0.161*	*0.078*	*0.280*	*–0.151*	*0.200*	*0.538*	*0.143*	*0.144*	*0.430*	*1.000*		
OC	*0.268*	*0.048*	*0.074*	*0.163*	*0.134*	*0.010*	*0.159*	*–0.180*	*–0.052*	*–0.221*	*0.196*	*0.066*	*0.044*	*0.040*	*0.207*	*0.431*	*0.351*	*–0.127*	*0.467*	*0.397*	*1.000*	
EC	*0.172*	*–0.005*	*0.080*	*–0.005*	*0.017*	*0.014*	*0.052*	*–0.009*	*0.272*	*–0.013*	*0.189*	*0.255*	*0.115*	*–0.014*	*0.124*	*0.145*	*0.151*	*0.145*	*0.446*	*0.255*	*0.415*	*1.000*

PBI = phosphorus buffering index; OC = organic carbon; EC = electrical conductivity

Notes:

1. Tissue test parameters are shown as regular text.
2. Soil test parameters are shown as italicised text.
3. Pale-blue shaded cells indicate there was a significant correlation at $P \leq 0.05$.
4. Positive numbers show a positive correlation and negative numbers show a negative correlation.

Appendix B Tissue and soil test data used in this study

Table B1 Tissue and soil test data for the 232 sample sites used in this study

	Tissue test parameters														Soil test parameters							
Project	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
SWCC	0.33	1.14	0.21	5.18	40.0	22.4	1.08	0.71	13.1	108	0.24	116	0.79	54.7	52	261.0	120	22.3	4.20	15	4.65	0.07
SWCC	0.24	2.28	0.20	4.00	40.0	19.2	0.76	0.67	10.3	184	0.28	110	0.54	36.4	47	213.8	304	14.4	4.60	45	4.88	0.13
SWCC	0.25	1.19	0.23	4.22	54.0	19.3	0.83	0.62	12.0	180	0.21	86	0.86	31.4	37	93.0	114	7.9	4.50	9	3.67	0.06
SWCC	0.27	0.80	0.25	4.51	46.0	18.2	0.99	0.79	10.3	168	0.22	107	0.95	38.3	38	127.4	43	10.2	4.50	11	4.02	0.07
SWCC	0.19	1.66	0.26	3.98	71.0	18.1	0.92	0.81	10.4	141	0.24	72	0.71	32.3	40	313.8	86	17.6	4.50	16	4.99	0.13
SWCC	0.22	1.84	0.24	4.13	50.0	19.8	1.12	0.89	10.7	144	0.26	83	0.76	36.5	19	151.1	88	17.0	4.90	8	3.44	0.10
SWCC	0.38	2.04	0.29	4.52	40.0	13.8	1.01	1.06	8.5	100	0.31	45	0.58	30.4	31	155.4	111	13.6	5.40	11	4.52	0.11
SWCC	0.31	1.38	0.24	4.56	40.0	19.1	1.32	0.82	11.0	165	0.28	138	0.55	32.8	28	91.0	346	29.3	4.50	92	5.16	0.29
SWCC	0.28	2.77	0.25	4.87	56.0	13.1	0.92	1.55	9.7	737	0.28	39	0.44	23.5	28	62.3	113	8.2	5.30	8	3.31	0.14
SWCC	0.42	2.84	0.32	4.99	210.0	17.8	0.66	1.53	10.0	1136	0.22	80	0.66	40.0	94	484.6	118	25.5	4.70	19	4.42	0.18
SWCC	0.45	2.23	0.30	3.94	40.0	17.7	2.26	1.84	4.7	126	0.27	32	0.73	22.8	62	122.1	77	16.0	7.40	5	4.84	0.23
SWCC	0.48	1.58	0.32	4.39	43.4	25.2	3.06	1.43	5.6	122	0.35	33	0.74	27.6	68	162.4	89	20.2	7.50	6	4.36	0.28
SWCC	0.36	2.04	0.28	4.44	53.0	19.9	1.08	0.73	7.7	317	0.28	39	0.64	33.0	55	328.0	88	15.3	4.80	15	4.72	0.13
SWCC	0.34	1.74	0.29	5.10	78.0	19.8	1.07	0.74	10.3	197	0.27	49	0.57	34.0	35	364.6	122	12.9	5.40	14	4.95	0.12
SWCC	0.29	2.17	0.32	4.60	40.0	23.9	1.04	0.88	9.9	245	0.29	116	0.65	50.0	30	721.1	165	41.1	5.10	40	5.66	0.21
SWCC	0.38	1.99	0.26	5.34	42.2	19.0	1.00	0.68	8.9	562	0.26	50	0.42	73.0	94	343.7	180	24.7	5.30	22	5.33	0.17
SWCC	0.31	1.53	0.28	5.04	51.0	22.0	1.24	0.69	11.3	176	0.25	51	0.59	30.9	42	577.4	133	26.9	5.20	19	4.28	0.19
SWCC	0.35	1.43	0.29	5.34	79.0	21.0	1.11	0.61	9.2	339	0.27	46	0.62	35.5	35	379.0	108	13.6	5.20	13	4.53	0.17
SWCC	0.40	1.03	0.30	4.95	40.0	15.9	0.89	0.80	11.4	371	0.17	108	0.52	42.3	30	391.2	132	12.2	4.60	20	5.01	0.07
SWCC	0.43	2.01	0.28	4.84	40.0	15.9	0.81	0.84	10.8	82	0.23	121	0.48	46.3	58	241.8	191	12.7	4.40	20	4.97	0.11

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
SWCC	0.34	1.11	0.29	5.25	40.0	18.1	1.20	0.98	13.0	261	0.23	81	0.76	46.6	25	238.5	72	9.2	4.80	13	3.77	0.11
SWCC	0.35	0.82	0.29	4.99	40.0	17.3	1.13	1.11	12.6	99	0.27	97	0.96	55.2	20	94.0	95	11.8	4.60	18	4.10	0.11
SWCC	0.38	1.45	0.30	4.46	58.1	17.5	0.79	0.79	14.0	376	0.24	125	0.83	51.1	44	206.0	139	13.1	4.40	34	5.18	0.12
SWCC	0.34	1.84	0.25	4.63	407.0	16.9	1.42	1.18	5.8	133	0.23	33	0.62	33.9	61	56.4	93	14.9	5.60	8	3.95	0.13
SWCC	0.32	1.68	0.22	4.33	40.0	20.7	0.96	1.02	4.1	115	0.20	30	0.77	20.9	29	69.6	87	20.0	5.40	10	4.60	0.17
SWCC	0.34	2.13	0.30	4.70	182.0	18.1	1.03	1.35	8.3	2002	0.26	55	0.70	32.5	38	141.7	150	16.4	5.90	24	3.43	0.18
SWCC	0.31	1.73	0.28	4.87	69.8	18.3	0.92	0.77	4.6	6574	0.25	64	0.63	29.3	23	161.5	78	12.6	5.40	7	3.42	0.14
SWCC	0.35	1.59	0.29	5.06	118.0	19.5	0.94	1.29	18.4	1403	0.28	98	1.06	43.5	43	157.5	124	12.8	5.40	22	4.30	0.14
SWCC	0.29	1.94	0.27	4.71	40.0	24.3	1.05	1.31	6.7	135	0.26	54	1.11	36.1	47	185.8	67	22.0	5.30	11	3.63	0.20
SWCC	0.43	1.78	0.32	5.35	75.6	19.2	0.86	1.17	9.3	288	0.28	76	0.97	36.3	33	178.0	56	14.3	5.10	9	4.00	0.13
SWCC	0.28	1.40	0.24	4.36	40.0	22.0	0.92	1.18	9.2	239	0.19	55	1.10	32.3	40	291.0	47	19.1	5.40	12	5.12	0.08
SWCC	0.27	1.69	0.25	4.00	40.0	22.9	1.68	1.00	3.8	126	0.27	63	0.79	35.2	13	95.8	85	12.5	5.00	13	5.52	0.11
SWCC	0.23	1.26	0.19	3.54	40.0	19.2	1.26	0.77	4.5	242	0.23	57	0.66	21.7	18	109.0	113	15.3	4.80	19	4.43	0.15
SWCC	0.23	1.53	0.21	3.58	40.0	18.1	1.59	0.77	3.6	295	0.23	54	0.62	20.1	26	231.9	76	16.7	5.20	12	4.30	0.14
SWCC	0.20	1.18	0.20	3.66	40.0	20.1	1.44	0.76	4.6	139	0.20	49	0.72	23.3	16	57.4	77	8.5	5.20	26	4.81	0.12
SWCC	0.28	1.60	0.27	4.47	40.0	19.5	1.49	0.80	12.2	220	0.24	47	0.69	26.7	30	210.3	65	21.4	5.80	12	4.87	0.16
SWCC	0.26	2.25	0.30	4.84	150.5	19.4	1.01	1.25	10.7	148	0.23	51	0.72	28.6	47	169.6	104	15.5	4.90	16	3.65	0.14
SWCC	0.25	1.94	0.22	5.54	40.0	19.2	1.05	0.63	10.8	100	0.21	63	0.53	29.8	18	178.7	70	8.6	4.90	7	3.29	0.08
SWCC	0.33	2.12	0.32	5.19	171.0	19.5	1.03	1.04	10.6	116	0.23	39	0.55	27.9	30	153.2	67	12.8	5.20	8	3.97	0.10
SWCC	0.36	2.60	0.30	5.26	323.0	18.4	0.90	0.79	6.0	112	0.23	37	0.43	25.8	35	117.1	68	10.0	5.20	7	3.86	0.08

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
SWCC	0.26	1.43	0.30	5.20	214.0	19.5	1.09	1.06	10.6	88	0.24	42	0.83	29.7	55	274.5	106	18.8	4.90	12	4.38	0.13
SWCC	0.32	1.91	0.19	4.07	40.0	17.9	1.29	0.62	8.2	69	0.29	47	0.58	40.5	45	115.1	171	10.3	4.90	22	3.91	0.12
SWCC	0.29	2.31	0.25	4.16	40.0	19.4	1.38	0.86	7.2	150	0.26	44	0.56	19.3	21	136.7	101	7.1	4.90	8	3.38	0.07
SWCC	0.41	1.13	0.29	3.74	121.5	13.5	1.30	1.33	8.0	273	0.28	86	1.05	22.0	47	226.6	58	13.0	4.50	13	4.32	0.10
SWCC	0.43	2.18	0.42	5.06	167.3	21.9	1.48	1.62	14.3	113	0.29	77	1.02	37.2	49	165.2	61	17.7	5.30	13	4.04	0.11
SWCC	0.31	1.35	0.27	4.25	42.6	18.3	1.81	1.23	9.6	119	0.26	49	0.93	22.4	39	176.8	50	17.8	5.50	15	4.01	0.12
SWCC	0.47	2.75	0.30	4.12	46.2	16.7	1.14	1.39	8.6	98	0.26	90	0.70	34.2	50	53.2	140	13.1	4.00	24	4.54	0.13
SWCC	0.36	1.85	0.23	4.14	40.0	20.9	1.15	0.86	4.1	104	0.24	43	0.74	33.1	78	137.1	126	11.9	4.50	11	5.39	0.13
SWCC	0.33	2.43	0.27	4.29	40.0	18.1	1.08	1.24	6.5	144	0.25	60	0.68	27.9	63	138.6	201	46.3	4.70	18	5.28	0.36
SWCC	0.35	2.20	0.24	4.09	40.0	19.4	1.05	0.86	9.1	380	0.20	38	0.95	22.0	23	302.1	215	46.3	6.20	10	6.03	0.34
SWCC	0.28	2.00	0.28	3.47	40.0	14.6	0.98	1.61	8.6	90	0.29	109	0.70	20.6	32	94.4	100	11.1	6.50	8	5.28	0.15
SWCC	0.32	2.55	0.29	4.14	81.0	20.2	1.12	1.56	8.0	399	0.22	60	0.61	25.8	28	475.6	285	127.2	6.30	51	5.35	0.62
SWCC	0.36	0.98	0.17	3.84	40.0	15.2	1.36	1.02	9.6	228	0.30	103	0.72	65.0	35	18.5	61	5.0	5.10	6	1.33	0.05
SWCC	0.27	1.75	0.20	3.31	40.0	17.5	1.13	0.91	10.8	374	0.29	114	0.69	53.0	19	15.5	42	4.1	5.10	4	1.05	0.05
SWCC	0.18	1.50	0.30	3.30	40.0	18.7	1.26	0.90	9.8	325	0.25	47	0.78	26.2	20	144.7	127	10.0	4.70	20	3.99	0.12
SWCC	0.27	2.02	0.33	4.59	74.0	21.3	1.19	1.22	14.5	493	0.26	52	1.03	33.9	55	386.6	100	17.1	4.50	18	4.14	0.14
SWCC	0.42	2.36	0.35	4.87	192.0	16.7	1.24	1.34	9.6	111	0.35	74	0.49	50.8	36	165.4	131	20.2	5.10	25	5.27	0.13
SWCC	0.37	2.15	0.30	4.85	55.0	18.1	0.93	1.35	7.0	142	0.29	59	0.83	41.5	30	230.4	128	18.2	5.00	16	3.89	0.13
SWCC	0.33	1.32	0.27	3.79	52.6	14.7	0.92	0.64	17.7	3802	0.22	121	0.70	27.7	55	230.3	66	4.6	5.50	10	3.14	0.04
SWCC	0.38	1.98	0.28	4.19	54.0	16.5	0.96	0.65	11.8	750	0.24	59	0.50	40.9	70	98.1	152	13.1	5.20	19	3.29	0.10

(continued)

Table B1 continued

	Tissue test parameters														Soil test parameters							
Project	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
SWCC	0.32	2.28	0.43	3.93	40.0	17.1	0.97	0.54	10.6	1893	0.23	34	0.25	27.4	85	234.3	182	8.2	6.00	11	3.43	0.10
SWCC	0.29	1.78	0.38	3.29	40.0	14.3	0.98	0.43	12.4	3714	0.18	43	0.22	34.6	69	289.2	322	12.4	6.50	15	3.28	0.13
SWCC	0.39	2.00	0.27	4.48	43.5	16.4	0.96	0.59	12.0	273	0.24	45	0.56	39.2	74	131.3	137	9.1	5.00	12	3.38	0.08
SWCC	0.40	2.66	0.28	4.24	40.0	17.1	1.09	0.76	8.5	119	0.25	31	0.25	28.6	84	105.3	225	6.7	6.00	9	3.25	0.09
SWCC	0.29	1.97	0.50	4.59	40.0	19.7	0.86	1.93	13.8	298	0.27	107	1.43	53.0	19	147.3	100	11.0	4.50	11	4.36	0.07
SWCC	0.40	2.00	0.37	4.32	40.0	16.9	0.88	1.47	9.8	238	0.27	95	0.94	44.8	38	127.4	43	10.2	4.50	11	4.02	0.07
SWCC	0.36	2.02	0.34	4.17	40.0	14.4	0.99	1.76	8.4	109	0.25	40	1.13	34.5	60	213.0	158	26.1	4.50	16	4.73	0.13
SWCC	0.32	1.25	0.22	4.64	40.0	21.5	1.11	0.53	10.4	126	0.24	82	0.83	65.0	16	55.2	97	11.8	4.20	23	5.38	0.13
SWCC	0.27	1.73	0.25	4.43	40.8	19.5	0.94	0.73	14.2	1270	0.20	45	0.68	31.0	28	62.3	113	8.2	5.30	8	3.31	0.14
SWCC	0.26	1.60	0.24	4.72	40.0	19.2	1.00	0.82	12.5	226	0.23	58	0.78	38.0	94	484.6	118	25.5	4.70	19	4.42	0.18
SWCC	0.30	1.88	0.25	4.65	122.0	19.6	0.92	0.75	12.6	231	0.21	52	0.70	29.9	19	119.7	92	15.8	5.80	14	4.39	0.17
SWCC	0.27	1.75	0.25	4.70	40.0	19.1	0.92	0.86	11.9	141	0.21	102	0.81	41.8	28	279.2	199	23.4	4.30	28	6.15	0.14
SWCC	0.33	1.46	0.26	4.93	43.0	20.5	0.97	0.86	11.4	301	0.21	65	0.90	35.8	45	270.7	115	9.9	4.60	25	5.07	0.13
SWCC	0.28	1.91	0.25	3.91	40.0	16.2	1.24	1.01	7.1	79	0.24	31	0.67	26.0	13	50.2	45	10.0	5.10	5	3.95	0.07
SWCC	0.30	1.58	0.24	4.19	40.0	16.2	1.36	0.92	5.3	80	0.25	32	0.63	29.0	17	81.3	55	7.6	5.40	6	3.85	0.07
SWCC	0.26	1.40	0.22	3.80	40.0	15.4	1.37	0.87	5.7	85	0.30	39	0.64	29.0	12	49.1	61	5.7	5.50	5	3.73	0.07
SWCC	0.33	1.58	0.26	3.93	40.0	15.5	1.08	0.89	5.5	304	0.26	44	0.61	31.0	28	73.4	62	8.0	5.10	7	3.67	0.08
SWCC	0.32	2.50	0.27	4.36	40.0	20.8	1.25	0.90	8.2	132	0.26	51	0.55	33.0	25	79.9	74	7.2	5.20	7	3.83	0.07
SWCC	0.31	1.85	0.28	4.22	40.0	17.6	1.42	0.91	6.0	101	0.28	40	0.58	30.0	10	83.7	69	7.3	5.20	5	3.61	0.07
SWCC	0.33	1.05	0.20	4.56	40.0	21.1	1.09	0.85	12.7	186	0.26	49	0.99	43.0	40	67.3	65	7.6	5.20	13	3.60	0.09

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
SWCC	0.18	2.27	0.22	4.29	43.0	20.6	1.38	0.96	11.8	128	0.23	72	0.56	45.5	36	81.6	116	10.5	5.00	11	4.86	0.10
SWCC	0.18	1.41	0.24	4.01	40.0	18.9	1.88	0.64	10.4	174	0.21	70	0.58	31.0	46	97.2	119	14.1	4.50	13	3.78	0.10
SWCC	0.25	1.55	0.25	4.50	40.0	21.0	1.13	0.91	13.8	114	0.25	104	0.90	33.0	50	209.4	106	15.3	4.60	12	4.63	0.12
SWCC	0.27	1.48	0.27	3.65	40.0	20.5	1.69	0.85	11.5	99	0.29	38	0.89	30.0	35	52.9	138	15.9	4.20	22	4.86	0.16
SWCC	0.28	2.47	0.24	3.76	40.0	13.6	0.63	0.90	12.1	980	0.26	155	0.47	23.9	44	383.7	221	29.1	4.40	29	3.90	0.14
SWCC	0.27	1.90	0.23	4.04	40.0	16.1	0.61	0.82	11.8	1119	0.22	97	0.69	22.9	41	228.1	336	12.2	4.60	18	4.03	0.11
SWCC	0.38	1.74	0.22	3.51	40.0	13.4	1.12	0.61	4.8	649	0.23	62	0.38	21.3	58	99.1	132	7.2	4.60	11	3.27	0.07
SWCC	0.32	2.23	0.23	3.57	40.0	15.0	0.60	0.74	11.8	1302	0.22	117	0.53	24.7	30	240.1	227	14.2	4.60	16	4.39	0.10
SWCC	0.37	1.49	0.27	3.78	40.0	15.5	0.91	0.73	13.8	1085	0.23	98	0.69	26.2	52	451.7	432	11.9	4.70	14	5.11	0.10
SWCC	0.41	1.27	0.25	3.81	40.0	18.4	1.07	0.60	4.6	504	0.24	67	0.62	36.0	58	110.9	107	8.3	4.60	11	3.92	0.09
SWCC	0.26	1.73	0.23	3.51	40.0	12.6	0.75	0.64	9.9	647	0.30	94	0.38	20.6	32	270.4	361	21.0	4.70	17	4.27	0.12
SWCC	0.32	1.56	0.25	3.74	40.0	14.0	0.80	0.61	10.1	1072	0.30	109	0.49	28.5	41	303.9	303	19.0	4.30	18	4.98	0.09
SWCC	0.30	1.94	0.26	3.84	40.0	14.0	0.96	0.52	11.2	560	0.35	84	0.33	15.5	19	114.5	141	7.8	4.50	9	3.15	0.09
SWCC	0.22	1.40	0.24	3.64	40.0	18.7	0.78	0.68	11.1	1018	0.35	55	0.60	24.7	17	196.0	103	15.4	4.60	25	3.84	0.09
SWCC	0.38	2.59	0.27	4.10	40.0	18.2	1.62	0.55	3.2	84	0.31	62	0.27	39.0	13	1.0	190	14.3	4.20	51	5.52	0.16
SWCC	0.47	2.20	0.23	4.36	44.0	19.6	1.13	0.75	8.8	79	0.33	48	0.47	48.0	14	1.0	181	12.6	4.40	24	5.31	0.12
SWCC	0.48	2.23	0.22	4.54	40.0	20.4	1.51	0.71	6.2	57	0.35	59	0.48	52.0	14	33.2	127	10.1	4.40	15	5.28	0.12
SWCC	0.36	2.83	0.29	4.62	106.0	17.4	0.69	0.86	11.9	280	0.25	109	0.41	50.7	68	374.4	273	22.3	4.40	63	5.82	0.16
SWCC	0.42	2.31	0.31	4.64	40.0	15.2	0.71	0.83	13.2	160	0.27	136	0.46	113.7	50	502.4	192	27.1	4.50	37	5.58	0.16
SWCC	0.34	2.23	0.26	5.00	272.8	17.2	0.81	0.82	10.7	113	0.28	85	0.37	71.5	28	194.3	177	15.5	4.50	28	4.94	0.12

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
SWCC	0.37	1.69	0.26	5.10	40.9	16.5	0.79	0.57	12.1	411	0.22	90	0.49	44.0	45	480.1	125	14.6	4.70	24	4.73	0.15
SWCC	0.34	1.73	0.25	4.29	40.0	13.6	0.53	0.76	10.4	143	0.20	77	0.65	47.7	74	296.9	146	13.4	4.00	40	5.46	0.10
SWCC	0.30	0.86	0.20	3.71	40.0	17.5	1.01	0.71	7.7	119	0.20	52	0.87	33.5	64	401.3	84	17.0	4.30	34	5.33	0.10
WFNM	0.21	1.87	0.22	3.68	40.0	22.2	1.52	1.04	6.7	144	0.30	41	1.08	23.2	38	233.3	118	12.3	5.50	–	–	0.20
WFNM	0.41	2.86	0.31	5.23	40.0	25.2	1.02	0.60	10.2	160	0.27	87	0.50	25.5	13	25.9	206	5.4	5.70	–	–	0.10
WFNM	0.25	1.19	0.22	4.44	40.0	21.5	1.07	0.57	12.6	551	0.25	44	0.87	24.6	41	363.7	105	14.6	4.90	–	–	0.14
WFNM	0.44	1.41	0.28	5.06	40.0	18.6	1.06	0.55	9.0	721	0.27	65	0.74	26.4	36	81.5	109	8.3	5.30	–	–	0.07
WFNM	0.32	1.13	0.23	3.80	40.0	19.3	1.59	1.04	8.2	182	0.28	51	1.36	17.9	28	98.7	110	8.9	5.90	–	–	0.04
WFNM	0.19	1.71	0.26	3.46	110.5	25.6	1.38	0.80	13.3	471	0.26	53	0.74	37.8	22	212.8	121	11.9	6.10	–	–	0.01
WFNM	0.15	2.71	0.23	3.38	80.6	22.5	1.33	0.83	11.2	135	0.28	50	0.36	31.6	30	197.5	183	11.6	4.90	–	–	0.12
WFNM	0.15	1.67	0.20	2.91	40.0	20.3	1.13	0.76	10.5	114	0.30	53	0.61	33.3	43	203.8	189	11.7	4.90	–	–	0.13
WFNM	0.20	1.23	0.25	4.04	40.0	22.3	1.49	1.34	7.4	106	0.33	52	1.40	39.2	36	114.2	116	9.4	4.10	–	–	0.64
WFNM	0.13	1.40	0.27	3.30	40.0	21.6	1.54	0.81	10.5	103	0.31	56	0.91	38.8	24	248.1	160	12.6	4.60	–	–	0.39
WFNM	0.27	1.66	0.15	2.64	40.0	19.3	2.05	0.53	6.5	91	0.40	23	0.35	38.7	145	73.4	220	8.0	5.00	–	–	0.12
WFNM	0.37	2.62	0.25	4.01	40.0	22.1	0.93	0.72	10.2	565	0.26	55	0.40	45.5	133	125.9	420	9.8	6.50	–	–	0.20
WFNM	0.31	1.70	0.24	4.71	40.0	24.8	0.74	0.96	8.9	114	0.35	55	0.76	25.7	23	169.9	229	10.9	5.50	–	–	0.48
WFNM	0.44	1.93	0.27	5.04	40.0	23.5	0.78	1.17	8.4	162	0.41	76	0.76	30.2	39	173.6	224	11.0	5.60	–	–	0.58
WFNM	0.31	2.19	0.26	4.74	40.0	20.2	1.23	0.45	8.4	308	0.22	31	0.32	28.3	38	109.8	130	9.3	5.20	–	–	0.11
WFNM	0.26	1.76	0.21	3.93	40.0	15.4	1.24	0.48	6.5	83	0.26	72	0.36	37.4	26	18.7	104	4.7	4.20	–	–	0.08
WFNM	0.35	2.12	0.21	4.36	40.0	21.1	1.12	0.75	5.1	105	0.41	72	0.45	43.8	16	7.3	157	3.3	4.20	–	–	0.10

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
WFNM	0.33	2.50	0.22	4.38	40.0	23.1	1.26	0.68	6.3	123	0.42	56	0.51	47.6	21	1.0	135	1.6	4.30	–	–	0.07
WFNM	0.41	2.17	0.24	4.39	40.0	19.1	0.84	0.57	10.1	705	0.29	53	0.44	35.0	11	18.6	138	4.7	5.40	–	–	0.09
WFNM	0.38	2.21	0.24	4.46	40.0	20.2	0.87	0.55	9.9	288	0.29	59	0.39	35.2	9	12.6	161	4.1	5.70	–	–	0.15
WFNM	0.36	1.81	0.26	4.98	98.0	25.3	0.65	1.12	10.1	177	0.47	77	0.93	36.3	18	559.7	167	17.2	5.00	–	–	0.63
WFNM	0.36	2.49	0.24	4.61	40.0	23.3	0.62	1.00	9.4	145	0.41	51	0.50	28.6	21	318.4	152	13.9	5.00	–	–	0.52
WFNM	0.22	2.44	0.19	3.30	45.2	25.4	0.99	1.04	9.1	179	0.34	40	0.68	38.1	32	213.3	100	11.9	4.30	–	–	0.14
WFNM	0.27	1.64	0.23	4.46	40.0	21.2	1.35	0.63	9.1	194	0.28	51	0.65	43.0	55	188.0	186	11.4	4.30	–	–	0.20
WFNM	0.20	1.69	0.22	3.87	40.0	22.4	0.78	0.64	13.1	249	0.32	88	0.68	41.7	20	173.0	163	11.0	4.20	–	–	0.15
WFNM	0.19	1.63	0.20	3.13	86.0	24.0	0.79	0.92	10.8	271	0.32	72	0.88	39.1	18	258.6	128	12.8	4.20	–	–	0.11
WFNM	0.19	1.73	0.21	3.62	40.0	22.1	0.86	0.68	11.5	157	0.33	79	0.64	40.1	15	125.4	130	9.8	4.10	–	–	0.11
WFNM	0.23	2.24	0.23	4.13	144.6	24.2	0.77	0.83	12.1	157	0.35	76	0.61	39.7	13	121.0	142	9.6	4.00	–	–	0.10
WFNM	0.24	2.20	0.18	3.55	40.0	24.0	1.08	0.79	7.5	71	0.37	46	0.51	30.6	27	45.2	182	6.6	4.40	–	–	0.09
WFNM	0.28	2.56	0.17	3.42	40.0	23.0	0.92	1.01	7.8	77	0.32	44	0.46	33.7	32	35.5	127	6.1	4.20	–	–	0.08
WFNM	0.29	2.18	0.23	4.22	40.0	22.1	1.22	0.99	11.5	88	0.31	55	0.60	52.6	25	83.1	115	8.3	4.00	–	–	0.09
WFNM	0.33	1.46	0.31	4.39	40.0	20.1	0.70	0.82	14.8	2105	0.36	81	0.98	38.7	44	151.1	148	10.5	5.10	–	–	0.27
WFNM	0.27	2.29	0.27	4.52	40.0	21.0	1.09	0.47	14.5	253	0.26	172	0.49	39.7	47	334.0	203	14.1	4.70	–	–	0.20
WFNM	0.20	1.96	0.23	3.84	40.0	19.2	0.85	0.71	11.9	255	0.35	123	0.64	31.5	26	274.6	177	13.1	5.00	–	–	0.47
WFNM	0.35	2.04	0.33	5.15	296.8	20.8	1.11	0.73	13.8	172	0.24	37	0.77	30.4	57	394.9	172	15.0	5.30	–	–	0.13
WFNM	0.36	1.84	0.27	4.21	40.0	24.7	0.75	0.70	12.8	453	0.25	33	0.92	34.7	41	451.3	134	15.8	5.70	–	–	0.11
WFNM	0.33	0.92	0.24	4.18	40.0	22.6	0.75	0.47	13.4	184	0.23	32	1.16	46.7	62	480.1	126	16.2	5.90	–	–	0.11

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
WFNM	0.42	2.02	0.28	4.48	40.0	26.2	1.49	0.58	11.5	125	0.29	64	0.90	39.9	38	159.2	162	10.7	5.60	–	–	0.40
WFNM	0.36	2.53	0.24	4.81	40.0	21.2	0.89	0.54	15.2	438	0.25	99	0.42	28.8	120	196.7	227	11.6	4.50	–	–	0.10
WFNM	0.50	2.26	0.19	4.23	40.0	22.5	0.99	0.33	5.9	221	0.32	67	0.36	47.6	21	36.5	102	6.1	5.00	–	–	0.44
WFNM	0.53	3.05	0.21	4.21	40.0	18.9	0.99	0.36	5.8	181	0.28	51	0.28	51.1	98	71.1	319	7.9	5.50	–	–	0.23
WFNM	0.18	2.01	0.21	3.60	40.0	23.4	1.67	0.89	12.2	119	0.33	76	0.66	29.1	52	168.1	203	10.9	4.80	–	–	0.18
WFNM	0.30	1.84	0.24	4.22	40.0	22.0	1.64	0.87	10.9	242	0.33	33	0.81	63.5	45	44.2	157	6.6	4.90	–	–	1.01
WFNM	0.46	2.37	0.28	5.09	40.0	23.0	0.91	1.10	11.1	1440	0.30	135	0.60	30.0	59	250.8	184	12.7	5.90	–	–	0.36
WFNM	0.42	3.08	0.28	5.31	182.3	27.2	0.81	0.85	10.1	915	0.26	188	0.30	25.9	52	423.4	324	15.4	5.40	–	–	0.24
WFNM	0.36	1.72	0.50	5.27	161.2	21.3	1.49	0.94	17.6	167	0.26	172	0.60	52.8	55	323.8	276	14.0	5.70	–	–	0.13
WFNM	0.17	2.09	0.17	2.83	40.0	22.3	1.36	0.84	8.2	123	0.31	34	0.65	29.8	27	195.7	196	11.5	5.10	–	–	0.14
WFNM	0.32	1.69	0.26	4.49	40.0	21.9	0.89	0.52	13.4	187	0.22	105	0.68	32.9	73	317.9	278	13.9	5.80	–	–	0.19
WFNM	0.25	1.49	0.19	3.69	40.0	21.1	1.33	0.63	9.7	156	0.26	45	0.83	42.4	19	25.8	107	5.4	5.10	–	–	0.38
WFNM	0.22	1.48	0.22	3.20	43.1	18.6	1.01	0.44	10.4	887	0.26	45	0.57	35.6	34	408.2	199	15.2	4.30	–	–	0.09
WFNM	0.29	0.94	0.25	4.50	40.0	21.7	0.93	1.31	12.5	108	0.30	91	1.45	47.2	36	55.6	116	7.2	5.60	–	–	1.23
WFNM	0.24	1.36	0.22	3.46	40.0	24.1	1.39	1.55	7.7	143	0.29	44	1.32	26.5	34	271.9	170	13.1	5.00	–	–	0.13
WFNM	0.23	2.21	0.22	3.23	40.0	24.9	1.21	0.93	3.9	129	0.30	19	0.50	35.9	8	54.2	142	7.1	5.20	–	–	0.07
WFNM	0.27	2.02	0.20	3.47	40.0	22.7	1.59	0.93	5.9	141	0.31	27	0.40	49.8	9	13.3	103	4.2	4.40	–	–	0.06
WFNM	0.44	2.14	0.26	4.44	40.0	20.8	1.01	0.80	7.9	203	0.34	107	0.67	38.2	73	43.3	122	6.5	4.40	–	–	0.09
WFNM	0.36	2.43	0.29	4.63	40.0	19.7	1.30	1.02	8.1	250	0.22	62	0.52	35.5	104	119.4	124	9.6	4.10	–	–	0.13
WFNM	0.28	1.84	0.21	4.03	40.0	23.0	1.58	0.66	7.4	149	0.32	37	0.46	52.1	25	12.1	160	4.0	5.20	–	–	0.12

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
WFNM	0.42	2.52	0.26	4.86	40.0	23.1	1.48	0.58	10.1	325	0.30	45	0.47	77.6	68	61.9	297	7.5	5.10	–	–	0.22
WFNM	0.30	1.68	0.26	3.96	48.3	21.4	2.20	0.58	7.6	88	0.45	22	0.49	36.6	26	42.9	166	6.5	5.50	–	–	0.12
WFNM	0.41	2.64	0.22	4.10	40.0	24.3	1.15	0.79	8.2	105	0.39	44	0.40	53.4	35	15.9	254	4.5	4.50	–	–	0.14
WFNM	0.35	1.94	0.21	4.25	40.0	24.2	1.03	0.92	9.3	123	0.31	51	0.65	41.3	31	36.6	152	6.1	4.60	–	–	0.10
WFNM	0.25	1.58	0.23	3.81	40.0	22.4	1.39	0.88	7.3	244	0.31	35	0.80	32.2	44	55.1	235	7.1	4.90	–	–	0.10
WFNM	0.14	2.08	0.20	3.26	46.0	19.3	1.17	0.61	8.5	114	0.23	39	0.37	25.0	16	375.1	112	14.8	4.70	–	–	0.06
WFNM	0.35	1.37	0.28	4.88	54.4	19.7	1.02	0.65	12.3	141	0.28	88	0.88	29.6	154	257.5	234	12.8	4.70	–	–	0.41
WFNM	0.22	1.30	0.23	3.75	40.0	20.4	1.06	1.14	10.5	97	0.32	64	0.98	38.9	36	475.5	129	16.1	4.60	–	–	0.14
WFNM	0.22	1.71	0.23	3.62	40.0	20.8	1.09	0.86	9.6	93	0.29	66	0.76	37.5	32	282.5	127	13.3	4.40	–	–	0.17
WFNM	0.23	1.93	0.20	3.34	40.0	23.8	1.16	1.02	9.1	77	0.29	50	1.11	43.3	41	256.3	115	12.8	4.70	–	–	0.21
WFNM	0.33	1.71	0.18	3.61	40.0	18.2	0.78	0.70	7.1	1763	0.32	126	0.51	27.6	84	269.4	204	13.0	5.20	–	–	0.39
WFNM	0.28	1.70	0.23	4.18	40.0	18.5	1.17	0.38	14.5	657	0.22	114	0.44	27.2	63	424.2	295	15.5	5.00	–	–	0.20
WFNM	0.32	2.04	0.24	4.54	40.0	17.7	1.07	0.50	13.1	237	0.21	142	0.47	33.6	135	360.4	312	14.5	5.40	–	–	0.11
WFNM	0.30	1.76	0.23	4.43	40.0	18.7	1.37	0.85	11.0	363	0.23	61	0.64	26.3	123	355.9	292	14.5	5.20	–	–	0.22
WFNM	0.35	1.03	0.25	4.62	40.0	20.2	1.06	0.83	12.7	321	0.21	37	0.90	43.6	129	371.8	141	14.7	6.20	–	–	0.20
WFNM	0.29	0.83	0.26	4.20	40.0	20.6	0.88	0.41	11.5	398	0.24	76	1.00	38.4	64	274.6	126	13.1	5.00	–	–	0.12
WFNM	0.30	1.64	0.25	4.81	40.0	18.5	1.05	0.56	13.5	199	0.23	109	0.68	43.4	33	362.9	151	14.6	4.20	–	–	0.21
WFNM	0.21	1.61	0.20	3.27	40.0	15.0	0.91	0.48	14.9	4851	0.22	42	0.38	29.0	59	216.3	169	12.0	6.00	–	–	0.18
WFNM	0.22	1.56	0.39	3.70	143.2	24.3	1.36	0.79	9.0	150	0.26	50	0.69	30.1	30	50.6	118	6.9	4.40	–	–	0.10
WFNM	0.10	1.16	0.17	2.43	40.0	20.2	1.45	0.53	10.2	178	0.28	88	0.77	34.5	10	340.6	136	14.2	4.70	–	–	0.04

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
WFNM	0.31	1.68	0.18	3.09	48.8	22.2	1.05	0.86	6.1	122	0.37	50	0.81	24.2	12	71.3	125	7.9	4.60	–	–	0.05
WFNM	0.22	2.26	0.20	3.73	43.0	19.4	1.34	0.66	4.8	152	0.35	62	0.36	22.6	8	127.4	119	9.8	5.10	–	–	0.04
WFNM	0.25	2.23	0.18	2.93	149.6	22.0	1.26	1.88	7.6	112	0.29	172	0.62	36.5	23	115.2	101	9.4	4.40	–	–	0.12
WFNM	0.32	2.27	0.25	4.11	67.2	26.2	1.43	1.18	5.7	170	0.28	32	0.49	23.1	115	274.7	109	13.1	4.70	–	–	0.18
WFNM	0.38	2.50	0.26	5.00	134.6	22.8	1.39	0.70	7.2	173	0.28	36	0.21	25.2	75	244.0	172	12.5	5.60	–	–	0.08
WFNM	0.46	2.56	0.23	3.63	167.1	25.7	0.98	0.98	5.5	83	0.39	21	0.73	35.8	40	19.6	206	4.8	4.30	–	–	0.19
WFNM	0.40	2.29	0.27	4.48	115.8	21.7	1.33	0.74	5.1	83	0.34	38	0.46	37.1	24	11.2	121	3.9	3.90	–	–	0.12
WFNM	0.30	1.97	0.24	4.36	67.7	19.6	1.21	0.83	6.6	200	0.36	35	0.59	32.8	25	66.6	221	7.7	4.90	–	–	0.11
WFNM	0.30	1.62	0.27	4.21	40.0	19.2	1.42	1.13	9.8	99	0.33	83	0.76	68.8	34	17.6	135	4.6	3.70	–	–	0.09
WFNM	0.29	1.77	0.21	3.50	64.6	21.6	1.68	0.90	7.5	75	0.32	28	0.59	47.9	20	10.8	180	3.9	4.10	–	–	0.05
WFNM	0.21	1.65	0.18	3.53	40.0	20.9	1.14	1.20	8.5	70	0.32	86	0.91	46.2	20	139.7	146	10.2	3.90	–	–	0.15
WFNM	0.20	1.67	0.17	3.04	146.8	21.8	1.01	1.22	8.5	125	0.22	37	1.01	20.5	31	140.1	114	10.2	5.00	–	–	0.13
WFNM	0.30	2.05	0.24	4.66	40.0	18.8	1.36	0.67	6.6	108	0.34	17	0.39	30.8	11	14.1	130	4.3	4.90	–	–	0.09
WFNM	0.24	1.72	0.19	3.67	40.0	22.9	1.48	0.66	8.9	98	0.26	30	0.44	31.9	29	57.3	144	7.3	5.10	–	–	0.10
WFNM	0.32	1.52	0.20	3.90	40.0	23.1	1.46	0.79	8.0	149	0.26	41	0.68	38.2	24	44.5	208	6.6	5.50	–	–	0.18
WFNM	0.28	2.01	0.21	4.11	40.0	20.7	1.60	1.15	6.2	87	0.33	51	0.69	21.5	24	133.8	110	10.0	5.70	–	–	0.23
WFNM	0.31	1.51	0.25	4.34	40.0	20.3	1.56	1.49	4.1	90	0.38	64	1.21	22.2	15	113.3	204	9.4	5.10	–	–	0.17
WFNM	0.23	1.66	0.20	3.58	40.0	18.6	1.41	0.77	5.0	88	0.28	26	0.53	16.4	24	104.9	119	9.1	5.80	–	–	0.06
WFNM	0.50	2.76	0.28	5.21	40.0	18.5	0.88	0.83	13.3	952	0.26	52	0.53	39.8	31	43.1	212	6.5	5.50	–	–	0.13
WFNM	0.47	2.18	0.32	4.51	40.0	18.9	0.81	0.88	8.1	305	0.25	54	0.77	28.1	27	36.1	249	6.1	5.50	–	–	0.10

(continued)

Table B1 continued

	Tissue test parameters														Soil test parameters							
Project	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
WFNM	0.35	1.98	0.24	4.03	40.0	17.0	0.85	0.46	8.6	418	0.25	60	0.28	33.2	12	26.7	160	5.4	5.60	–	–	0.11
WFNM	0.32	2.18	0.33	4.23	40.0	19.6	1.13	0.54	10.6	968	0.22	65	0.17	40.2	12	28.6	131	5.6	5.40	–	–	0.07
WFNM	0.27	2.26	0.22	3.47	40.0	16.4	1.16	0.41	9.3	283	0.23	49	0.14	37.6	21	16.7	122	4.6	5.30	–	–	0.06
WFNM	0.54	2.42	0.28	4.60	40.0	19.5	0.79	1.07	8.4	532	0.26	51	0.92	28.3	45	34.3	246	6.0	5.60	–	–	0.11
WFNM	0.32	2.00	0.25	4.24	40.0	18.0	1.16	0.44	9.6	400	0.20	39	0.18	33.0	11	33.5	135	5.9	5.30	–	–	0.06
WFNM	0.52	2.62	0.33	5.03	40.0	16.9	0.85	1.03	6.8	552	0.29	69	0.48	30.8	11	37.4	229	6.2	5.70	–	–	0.17
WFNM	0.38	2.88	0.23	3.78	40.0	21.1	0.86	0.46	8.9	149	0.24	59	0.20	41.8	10	14.7	125	4.3	5.20	–	–	0.06
WFNM	0.21	1.35	0.16	3.36	40.0	22.9	0.82	0.60	10.3	144	0.29	73	0.75	47.9	24	152.6	114	10.5	3.90	–	–	0.12
WFNM	0.20	1.32	0.21	4.09	40.0	22.0	0.91	0.53	11.9	116	0.24	57	0.75	38.9	18	104.7	119	9.1	3.90	–	–	0.07
WFNM	0.22	1.18	0.35	4.03	40.0	21.1	1.24	0.71	13.6	131	0.28	62	0.94	43.2	32	203.1	114	11.7	4.40	–	–	0.07
WFNM	0.27	1.99	0.18	3.40	111.5	19.2	0.97	0.73	7.6	70	0.37	105	0.40	36.9	29	32.3	166	5.8	3.90	–	–	0.07
WFNM	0.40	2.25	0.25	4.81	40.0	24.2	0.65	1.11	5.2	135	0.42	66	0.66	24.4	57	171.9	159	11.0	5.50	–	–	0.86
WFNM	0.37	2.63	0.28	4.72	40.0	18.7	1.27	0.51	10.5	142	0.23	62	0.18	29.7	157	151.1	672	10.5	5.40	–	–	0.10
WFNM	0.23	1.85	0.24	4.07	40.0	19.1	1.01	0.60	14.7	145	0.23	97	0.60	37.3	17	142.6	188	10.2	5.00	–	–	0.11
WFNM	0.17	1.46	0.23	4.06	40.0	16.0	0.86	0.46	14.7	531	0.20	91	0.47	29.8	11	244.1	147	12.5	4.70	–	–	0.13
WFNM	0.29	1.86	0.24	3.77	40.0	19.2	0.92	0.47	8.2	395	0.25	53	0.26	27.8	6	45.5	190	6.6	6.00	–	–	0.05
WFNM	0.25	2.19	0.26	4.16	40.0	19.1	1.07	0.55	6.4	162	0.28	55	0.36	32.8	8	33.0	207	5.9	6.90	–	–	0.14
WFNM	0.25	2.03	0.23	3.89	40.0	20.0	1.17	0.48	5.1	162	0.30	56	0.31	26.4	7	20.0	308	4.9	6.30	–	–	0.13
WFNM	0.29	2.23	0.25	4.49	40.0	20.6	1.31	0.57	8.1	185	0.22	51	0.29	42.0	7	9.3	156	3.6	5.90	–	–	0.05
WFNM	0.28	1.68	0.22	4.11	40.0	18.7	1.31	0.48	11.5	101	0.23	103	0.28	47.7	8	6.8	100	3.2	5.70	–	–	0.04

(continued)

Table B1 continued

Project	Tissue test parameters														Soil test parameters							
	P (%)	K (%)	S (%)	TN (%)	NO_3 (mg/kg)	B (mg/kg)	Ca (%)	Cl (%)	Cu (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Na (%)	Zn (mg/kg)	P (mg/kg)	PBI	K (mg/kg)	KCl-40 S (mg/kg)	pH_{Ca}	NH_3 (mg/kg)	OC (%)	EC (dS/m)
WFNM	0.31	1.99	0.27	4.16	40.0	18.3	1.07	0.47	8.3	266	0.25	95	0.33	40.5	9	17.0	128	4.6	5.10	–	–	0.03
WFNM	0.28	2.28	0.24	4.07	40.0	18.8	1.28	0.46	9.9	101	0.25	75	0.21	39.8	9	17.1	138	4.6	5.90	–	–	0.06
WFNM	0.34	1.89	0.24	4.29	40.0	17.0	1.34	0.50	8.1	143	0.25	73	0.24	35.1	6	17.3	140	4.6	5.70	–	–	0.04
WFNM	0.30	2.16	0.22	4.03	40.0	18.3	1.25	0.42	7.3	645	0.26	64	0.25	35.2	7	33.4	193	5.9	5.40	–	–	0.04
WFNM	0.32	1.45	0.28	4.60	40.0	22.7	1.40	0.84	8.1	112	0.30	30	0.99	42.0	21	25.6	151	5.3	4.00	–	–	0.19
WFNM	0.25	1.56	0.11	2.23	40.0	25.1	1.24	0.91	4.9	64	0.35	28	0.76	38.5	17	1.0	171	1.6	3.80	–	–	0.04
WFNM	0.27	1.02	0.23	4.10	40.0	22.8	1.42	1.08	7.6	93	0.32	44	1.33	36.8	25	1.0	134	1.6	3.70	–	–	0.08
WFNM	0.16	1.61	0.18	3.01	40.0	19.0	1.63	0.81	6.8	57	0.28	21	0.63	34.2	16	14.1	146	4.3	4.50	–	–	0.17
WFNM	0.22	1.88	0.23	3.72	40.0	21.6	1.70	0.97	8.2	125	0.25	37	0.77	34.8	27	151.2	155	10.5	5.50	–	–	0.18
WFNM	0.31	1.97	0.18	3.74	40.0	20.5	1.36	1.13	8.9	75	0.37	54	0.77	61.3	34	5.3	187	2.9	4.00	–	–	0.19
WFNM	0.27	2.13	0.19	3.07	40.0	20.0	1.34	1.02	8.8	121	0.32	42	0.54	49.6	43	14.5	159	4.3	4.40	–	–	0.09
WFNM	0.10	1.57	0.19	2.50	40.0	20.4	1.72	0.55	11.0	105	0.25	51	0.48	29.9	10	388.9	123	15.0	4.70	–	–	0.06

P = phosphorus; K = potassium; S = sulfur; TN = total nitrogen; NO_3 = nitrate; B = boron; Ca = calcium; Cl = chloride; Cu = copper; Fe = iron; Mg = magnesium; Mn = manganese; Na = sodium; Zn = zinc; PBI = phosphorus buffering index; KCl-40 S = sulfur soil test; NH_3 = ammonia; OC = organic carbon; EC = electrical conductivity; – = not assessed

Shortened forms

Short form	Long form
DPIRD	Department of Primary Industries and Regional Development
K	potassium
KCl-40 S	sulfur soil test (extracted in potassium chloride solution at 40°C)
P	phosphorus
pH_{Ca}	pH measured in calcium chloride
P_{90}	phosphorus response or yield at 90% of maximum production
PBI	phosphorus buffering index
S	sulfur
SWCC	South West Catchments Council
WA	Western Australia
WFNM	Whole farm nutrient mapping

References

Angell, K 1999, 'Fertilisers for pastures on sandy soils of the Swan Coatal Plain', *Bulletin 4357*, Agriculture Western Australia, Perth.

Blair, G, Chinoim, N, Lefroy, R, Anderson, G & Crocker, G 1991, 'A soil sulfur test for pastures and crops', *Soil Research*, vol. 29, no. 5, pp. 619–626.

Bolland, M, Russell, B & Weaver, D 2010, *Phosphorus for high rainfall pastures*, Department of Agriculture and Food, Western Australia, Perth.

Burkitt, L, Moody, P, Gourley, C & Hannah, M 2002, 'A simple phosphorus buffering index for Australian soils', *Australian Journal of Soil Research*, vol. 40, pp. 497–513.

Colwell, J 1965, 'An automatic procedure for the determination of phosphorus in sodium hydrogen carbonate extracts of soils', *Chemical Industry*, vol. 22, pp. 893–895.

Cope, J & Rouse, R 1973, 'Interpretation of soil test results', in L Walsh & J Beaton (eds), *Soil testing and plant analysis*, Soil Science Society of America, Inc, Madison, Wisconsin, USA, pp. 35–54.

Edwards, AC 1991, 'Soil acidity and its interactions with phosphorus availability for a range of different crop types', in RJ Wright, VC Baligar & RP Murrmann (eds), *Plant–soil interactions at low pH: developments in plant and soil sciences*, Springer, Netherlands, Dordrecht, vol 45, pp. 299–305.

Gourley, C, Melland, A, Waller, R, Awty, I, Smith, A, Peverill, K & Hannah, M 2007, 'Making better fertiliser decisions for grazed pastures in Australia', Department of Primary Industries, Melbourne, Victoria.

Gourley, C & Weaver, D 2012, 'Nutrient surpluses in Australian grazing systems management practices, policy approaches, and difficult choices to improve water quality', *Crop and Pasture Science*, vol. 63, no. 9, pp. 805–818.

Gourley, C, Weaver, D, Simpson, R, Aarons, S, Hannah, M & Peverill, K 2019, 'The development and application of functions describing pasture yield responses to phosphorus, potassium and sulphur in Australia using meta-data analysis and derived soil-test calibration relationships', *Crop and Pasture Science*, vol. 70, pp. 1065–1079.

McDowell, R, Dodd, RJ, Pletnyakov, P & Noble, A 2020, 'The ability to reduce soil legacy phosphorus at a country scale', *Frontiers in Environmental Science*, vol. 8, p. 6.

McGill, R, Tukey, J & Larsen, W 1978, 'Variations of box plots', *The American Statistician*, vol. 32, pp. 12–16.

Miles, N & Eckard, R 1991, 'Lime–phosphorus interactions in the growth of temperate pasture species on highly-weathered soils', *South African Journal of Plant and Soil*, vol. 8, no. 4, pp. 200–205.

Moore, G, Dolling, P, Porter, B & Leonard, L 1998, in G Moore (ed.), 'Soil guide: A handbook for understanding and managing agricultural soils', *Bulletin 4343*, Agriculture Western Australia, Perth.

Munns, D 1965, 'Soil acidity and growth of a legume. I. Interactions of lime with nitrogen and phosphate on growth of Medicago sativa L. and Trifolium subterraneum L.', *Australian Journal of Agricultural Research*, vol. 16, no. 5, pp. 733–741.

Rayment, G & Higginson, FR 1992, *Australian laboratory handbook of soil and water chemical methods*, Inkata Press Pty Ltd, Melbourne, Victoria.

Rayment, G & Lyons, D 2010, *Soil chemical methods – Australasia*, CSIRO Publishing, Collingwood, Victoria.

Reuter, D & Robinson, J 1997, *Plant analysis, an interpretation manual*, CSIRO publishing, Collingwood, Victoria.

Scanlan, CA, Brennan, RF, D'Antuono, MF & Sarre, GA 2017, 'The interaction between soil pH and phosphorus for wheat yield and the impact of lime-induced changes to soil aluminium and potassium', *Soil Research*, vol. 55, no. 4, pp. 341–353.

Schofield, R & Taylor, AW 1955, 'The measurement of soil pH 1', *Soil Science Society of America Journal*, vol. 19, no. 2, pp. 164–167.

Shoop, G, Brooks, C, Blaser, R & Thomas, G 1961, 'Differential responses of grasses and legumes to liming and phosphorus fertilization 1', *Agronomy Journal*, vol. 53, no. 2, pp. 111–115.

Simpson, R, Oberson, A, Culvenor, R, Ryan, M, Veneklaas, E, Lambers, H, Lynch, J, Ryan, P, Delhaize, E, Smith, F, Smith, S, Harvey, P & Richardson, A 2011, 'Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems', *Plant and Soil*, vol. 349, no. 1, pp. 89–120.

Truog, E 1948, 'Lime in relation to availability of plant nutrients', *Soil Science*, vol. 65, no. 1, pp. 1–8.

Walkley, A & Black, IA 1934, 'An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method', *Soil Science*, vol. 37, pp. 29–38.

Weaver, D & Reed, A 1998, 'Patterns of nutrient status and fertiliser practice on soils of the south coast of Western Australia', *Agriculture Ecosystems and Environment*, vol. 67, no. 1, pp. 37–53.

Weaver, D & Wong, M 2011, 'Scope to improve phosphorus (P) management and balance efficiency of crop and pasture soils with contrasting P status and buffering indices', *Plant and Soil*, vol. 349, no. 1–2, pp. 37–54.